"Memory loss" during mineral processing: Application to base metals traceability

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Julie Machault (1, 2, *), Luc Barbanson (1), Thierry Augé (2), Laurent Bailly (2) et Alexandre Felicio (3)

(1)Institut des Sciences de la Terre d'Orléans (ISTO) – Université d'Orléans/CNRS-INSU/BRGM – UMR 7327 – 1A rue de la Férollerie 45071 Orléans Cedex 2 France.

(2)Bureau des Ressources Géologiques et Minières (BRGM) – Direction des Géoressources (DGR/MIN) – 3 avenue Claude Guillemin BP 36009 45060 Orléans Cedex 2, France.

(3)SOMINCOR – Minas Neves Corvo – Santa Barbara de Padroes P-7780-909 Portugal

*Corresponding author. Tel.: +33 (0)2 38 49 27 64

E-mail address: j.machault@gmail.com

Abstract

Traceability of concentrates is required to introduce transparency in the trade of raw minerals. In this context traceability may be considered as a kind of inversion process: studying the product sold (i.e. the concentrate) in order to identify the original ore, in terms of ore deposit-type and if possible, location. The difficulty of making this inversion from concentrate toward bulk ore corresponds to the "memory loss" of the crude ore which occurs during mineral processing. Based on textural characterization and the chemical composition

of the material at different steps of processing, as well as the minimum residence corresponding to each step, an estimation of this "memory loss" is proposed and the relations between memory loss and global kinetic rate of flotation are established.

"Memory loss" calculations are applied to the Neves Corvo plant. Throughout the process, the parameter of memory loss increases respectively from 0 to 195.06 for Cu; 0 to 46.15 for Zn and 0 to 0.43 for Fe. The "global memory loss", namely as the "the experimental memory loss". For the Neves Corvo plant at the moment of the study this "experimental memory loss" was 14146 min for Cu, 3408 min for Zn and 36 min for Fe. The results show that "memory loss" is greater for Cu than for Zn, thus emphasizing the importance of secondary elements for traceability purposes.

Keywords: traceability, "memory loss", mineral processing, target minerals, Neves Corvo.

1 Introduction

The demand in mineral resources is increasing rapidly, but there is a lack of transparency in the trading of concentrated raw mineral materials. This is a concern of the French Ministry of Ecology, Sustainable Development and Energy (http://www.developpement-durable.gouv.fr/La-politique-des-ressources.html#s_curit_; Braux and Christmann, 2012; Christmann and al., 2012). Traceability of raw material is also an issue for the automobile manufacturer Renault (Schulz, 2012).

Control of trade in the mineral industry would be facilitated by traceability of concentrates. Further, as pointed out by Kvarnström and Oghazi (2008), traceability can also play an important role when a mixture of bulk ore from different mines, each with different characteristics, is treated: in some cases the use of such mixtures complicates subsequent mineral processing.

The traceability problem may be considered as a kind of inversion process: studying the product sold (i.e. the concentrate) to identify the original ore. The determination of the origin of a concentrate implies to involve up from the concentrate to the bulk ore, taking into account the transformation during mineral processing. In this study a new method, namely the "memory loss" method, is proposed to estimate the difficulty of realizing such an inversion that is to say which quantifies the loss of identifiable characteristics during mineral processing. In other words, the "memory loss" indicates the difficulty to realize an inversion from the concentrate toward the bulk ore. The "memory loss" method may also be useful, alongside other methods, as a tool to characterize a given mineral processing operation.

First, the "memory loss" method will be presented. Then its relation with sampling and flotation kinetics will be emphasized. Finally, an example taken from the Neves Corvo (Portugal) mineral plant will illustrate the use of the "memory loss" method.

2 The “memory loss” method

It could be useful first to recall some concepts concerning sampling for granular materials. A sampling method is described as equiprobable if, in a lot L, consisting of N fragments, all possible combinations of p fragments ($p<N$) have the same probability to form the sample E (Gy, 1996). This would occur if fragments were collected one by one and at random, and may also be achieved if the batch is homogenized (for example by mixing).

If an equiprobable sample is used to determine a characteristic of the lot, there will remain an incompressible error related to intrinsic properties of the material. This is the fundamental error of sampling related to the Constitution Heterogeneity (Gy, 1988). According to Gy, 1988, Constitution Heterogeneity is defined as the variance of h_j, where h_j is a parameter related to the fragment j and expressed as: $h_j = \left(\frac{a_j - a}{a}\right) \cdot \left(\frac{m_j}{\overline{m}}\right)$ with a_j the value of the characteristic within the fragment j, a the value of the characteristic within the lot, m_j the mass of the fragment j and $\overline{m}$ the average mass of the N fragments. In section 2.2, an analogy between "memory loss" and the parameter h_j of Gy's theory of particulate sampling theory is proposed.

The flow sheet of a mineral processing operation is always complex and is sometimes confidential. In order to compare either different treatments applied to similar ores or similar treatments applied to different ores, it is necessary to simplify the processing chain and extract the most crucial parameters. The proposed method does not attempt to describe the whole range of the numerous and complex phenomena involved in the mineral valuation process, but to provide a simplified holistic representation of the mineral treatment.

The mineral processing of a given ore can be considered as a process in which the memory characteristics of the bulk ore are removed. At a given step, namely i, of the process, this “loss” can be evaluated by a "memory loss” parameter (pml_i). For a given treatment the total estimated "memory loss" (ML) is defined. The "memory loss" calculated from the experimental data, will be called the experimental “memory loss" (ML_{exp}).

2.1 Definition of "memory loss" parameter plm_i

Let us consider a mineral processing operation of n steps. Each step is denoted with subscript i. t_i is the minimum residence time at step i and T_i is the value of a characteristic of the material flowing in the plant at this step. The characteristic can be: the metal content (primary or secondary, valuable or penalizing); the content in a main useful mineral or in gangue mineral; the grain size of a main useful mineral; or the content of chemical elements associated with the concentrated fraction. Finally, T_{BO} and T_C are the respective values of the characteristic in the bulk ore and concentrate. Note that when i = 0, t = 0 and $T_0 = T_{BO}$, and when i = n, $t = t_n$ and $T_n = T_C$.

We can define a parameter that estimates the "memory loss" of the bulk ore characteristic at step i for a given mineral processing operation:

$$pml_i = \left(\frac{T_i - T_{BO}}{T_{BO}}\right)^2 \quad (1).$$

To evaluate the “loss of memory” we choose to use a limited number of characteristics selected to facilitate the necessary measurements. In the parameter “memory loss”, the overall mass flow at each stage of the processing is not considered. However the chemical composition at each stage in the mineral processing is taken into account; indeed, according to equation 1, it is a part of the definition of “memory loss” at a given stage of the mineral processing.

For i = 0, t = 0, $T_0 = T_{BO}$ and then $pml_0 = 0$.

For i = n, $t = t_n$, $T_n = T_C$ and then $pml_n = \left(\frac{T_C - T_{BO}}{T_{BO}}\right)^2$.

It is worth noting that, for an effective mineral processing operation, the value of the "memory loss" increases during treatment. In the ideal case, the content of useful metal within

the concentrate is equal to the metal content in the useful mineral. We also use a minimum residence time, because each grain may remain in the circuit indefinitely. The minimum residence time corresponds to the nominal time of a given stage. A graphical representation of the "memory loss" parameter during mineral processing is given in figure 1.

During comminution, only the characteristics of fragments (i.e. size and shape) may vary. Oghazi et al. (2009) proposed a monitoring evolution of these characteristics for the case of iron ore grinding. Texture analysis provides information about the distribution and release of minerals for the different fractions (Oghazi et al., 2009).

2.2 Perfectly ineffective mineral processing, sampling theory and loss of memory

To compare different mineral processing, or similar mineral processing applied to a different ore, it is necessary to have an invariant reference whatever the treatment and/or the ore considered. This reference could be a perfectly ineffective mineral processing defined as: $\forall i$, $T_i = T_{BO}$, which imply: $\forall i$, $pml_i = \left(\frac{T_i - T_{BO}}{T_{BO}}\right)^2 = 0$. Note that a perfectly ineffective mineral processing is a perfect sampling process. Indeed at each stage of processing, the considered parameter is identical in the “tailings” and “concentrate” fractions.

According to the sampling theory of granular materials of Gy (1975), the contribution of a grain, namely j, to the value T_{BO} of the characteristic in the bulk ore can be estimated by: $h_j = \left(\frac{T_j - T_{BO}}{T_{BO}}\right) \cdot \left(\frac{m_j}{\overline{m}}\right)$ where T_j is the value of the characteristic in the grain j, m_j is the mass of the grain, and $\overline{m}$ is the average mass of grains. Then h_j is the product of a first term, which represents the departure between the grain j and the bulk ore with respect to the considered characteristic, and a second term taking into account the importance of the grain j within the bulk ore. The "memory loss" parameter (pml_i) equals the square of this first term of h_j.

Choosing the perfectly ineffective treatment provides a reference that is: 1) unambiguously defined, 2) easy to use, and 3) consistent whatever the processed ore or the considered mineral processing. Using a measured characteristic reference in the concentrate would be less convenient, because the deduced value always varies from one ore to another. Finally, selecting a reference involved in Gy's theory will allow further developments taking into consideration the sampling theory of granular materials of this author.

Whatever the residence time, a perfectly inefficient mineral processing operation is characterized by a null "memory loss"; the metal contents in the bulk ore, the concentrate and the residue are all equal by definition. In plot of figure 1, the values of the parameter of "memory loss", at each stage i, are therefore distributed along a horizontal line (figure 1).

2.3 Definition of the "memory loss" (ML) of the bulk ore characteristics during mineral processing

The "memory loss" (ML) of a bulk ore characteristic during a mineral processing is defined as:

$$ML = \int_0^{t_n} pml_i \cdot dt = \int_0^{t_n} \left(\frac{T_i - T_{BO}}{T_{BO}}\right)^2 \cdot dt \qquad (2)$$

where t is the minimum residence time. For t = 0, the value T of the studied characteristic is T_{BO} ; at time t, the value T of the studied characteristic is T_i ; at time $t = t_n$, the value T of the studied characteristic is T_C.

The integral of the "pml_i" function over minimum residence time (gray area in figure 1), represents the departure, with respect to a given characteristic (typically metal contents),

between the studied treatment and the case of a perfectly ineffective treatment (figure 1). Note that ML is expressed in units of time.

This integral function characterizes the mineral processing of a given mine, at a given time. This integral also estimates the difficulty of making the inversion from concentrated to bulk ore, and can be regarded as a way to express the error associated with this inversion.

The experimental “memory loss" (ML_{exp}) of a bulk ore characteristic during a mineral process with n steps, each denoted i and with a value T_i of the considered characteristic, is equal to :

$$ML_{exp} = \frac{1}{2} \cdot \sum_{i=1}^{n} \left(\left(\frac{T_i - T_{BO}}{T_{BO}} \right)^2 + \left(\frac{T_{i-1} - T_{BO}}{T_{BO}} \right)^2 \right) \cdot (t_i - t_{i-1}) \quad (3)$$

where t_i is the minimum residence time at step i.

2.4 Kinetics of flotation and "memory loss" of bulk ore characteristics during mineral processing

In case of a mineral processing using flotation techniques, the rate of "memory loss", should consider the kinetics of flotation. Thus, pml_i and ML will be expressed in terms of kinetic constants.

The laws of flotation kinetics, defined by analogy with the kinetics of chemical reactions, have been considered to be complex to use because of the numerous parameters involved (Blazy, 1970). Despite this difficulty, the overall operation of a mineral processing plant can be described by first order kinetics (Kelly and Spottiswood, 1990; Çilek, 2004). Kinetics of this order can be used to design many flotation circuits (Agar, 1987; Wills, 1997; Agar et al., 1998, Xu, 1998; Oliveira et al., 2001). But in some cases second-order kinetics are better to account for the experimental results (Yalcin and Kelebek, 2011). This set of

observations led Volkova (1947) and Nguyen and Schulze (2003) to consider that the flotation kinetics is of first order when the flotation of isolated minerals or a very diluted pulp (various-sized particles suspended in a liquid) is considered, and of second order for ores at low mineral concentrations or solid concentrated pulp. In summary, the reaction kinetics can be considered to be of order in the range 1 to 2 (Hernáinz and Calero, 1996; 2001).

In case of first order kinetics, the evolution of a bulk ore characteristic over time is: $\frac{dT}{dt} = k_1 \cdot T$ which after integration gives: $\ln\left(\frac{T_i}{T_{BO}}\right) = k_1 \cdot t$ (4)

or $\frac{T_i - T_{BO}}{T_{BO}} = e^{k_1 \cdot t} - 1$ (5).

According to (4), the k_1 coefficient is determined by measuring the slope of the regression line of the experimental points plotted as $\ln\left(\frac{T_i}{T_{BO}}\right)$ versus t. At t = 0, $T_i = T_{BO}$ and $\ln\left(\frac{T_i}{T_{BO}}\right) = 0$, and then the regression line intercepts the origin. The value of the correlation coefficient provides a measure of the fit of the experimental results for 1st order kinetics. In this case, using (1) and (5), the "memory loss" parameter at step i for a mineral processing operation (pml_i) can be written as :

$$pml_i = \left(\frac{T_i - T_{BO}}{T_{BO}}\right)^2 = (e^{k_1 \cdot t} - 1)^2 \quad (6).$$

ML_1 is the "memory loss" of a bulk ore characteristic during mineral processing with first order kinetics. Using (2) and (6), ML_1 may be expressed as:

$ML_1 = \int_{T_{BO}}^{T_i} \left(\frac{T_i - T_{BO}}{T_{BO}}\right)^2 \cdot dt = \int_0^t (e^{k_1 \cdot t} - 1)^2 \cdot dt = \int_0^t (e^{2k_1 \cdot t} - 2 \cdot e^{k_1 \cdot t} + 1) \cdot dt$ and finally

$$ML_1 = \frac{e^{2 \cdot k_1 \cdot t} - 4e^{k_1 \cdot t} + 2 \cdot k_1 \cdot t + 3}{2 \cdot k_1} \quad (7).$$

In case of a second order kinetics, the evolution of a bulk ore characteristic over time is:

$\frac{dT}{dt} = k_2 \cdot T^2$ and, after integration: $1 - \left(\frac{T_{BO}}{T_i}\right) = k_2 \cdot T_{BO} \cdot t$ (8).

Equation (8) can be rewritten as : $\frac{T_i - T_{BO}}{T_{BO}} = \frac{T_{BO} \cdot k_2 \cdot t}{1 - T_{BO} \cdot k_2 \cdot t}$ (9).

According to (8), in a plot of $\left(1 - \frac{T_{Bo}}{T_i}\right)$versus t, the slope of the regression line of the experimental points is equal to ($T_{BO}.k_2$). At t = 0, $T_i = T_{BO}$ and $\left(1 - \frac{T_{BO}}{T_i}\right) = 0$. Then the regression line intercepts the origin. The value of the correlation coefficient provides a measure of the fit of the experimental results for a second-order kinetics. Using (1) and (9) the "memory loss" parameter at step i for a mineral processing operation (pml_i), in case of second-order kinetics, can be written:

$$pml_i = \left(\frac{T_i - T_{BO}}{T_{BO}}\right)^2 = \left(\frac{T_{BO} \cdot k_2 \cdot t}{1 - T_{BO} \cdot k_2 \cdot t}\right)^2 = \left(\frac{1}{1 - T_{BO} \cdot k_2 \cdot t} - 1\right)^2 \quad (10).$$

ML_2 is the "memory loss" value of the bulk ore characteristics for a mineral processing for the case of second order kinetics. According to (2) and (10), ML_2 may be expressed as:

$$ML_2 = \int_{T_{BO}}^{T_i} \left(\frac{T_i - T_{BO}}{T_{BO}}\right)^2 \cdot dt = \int_0^t \left(\frac{1}{1 - T_{BO} \cdot k_2 \cdot t} - 1\right)^2 \cdot dt \ ;$$

$ML_2 = \int_0^t \left(\frac{1}{1 - T_{BO} \cdot k_2 \cdot t}\right)^2 \cdot dt - 2 \cdot \int_0^t \left(\frac{1}{1 - T_{BO} \cdot k_2 \cdot t}\right) \cdot dt + \int_0^t dt$ and finally:

$$\int_0^t \left(\frac{1}{1 - T_{BO} \cdot k_2 \cdot t}\right)^2 \cdot dt = -\frac{1}{T_{BO} \cdot k_2 \cdot (1 - T_{BO} \cdot k_2 \cdot t)} + \frac{1}{T_{BO} \cdot k_2}.$$

By changing the variable: $U = T_{BO} \cdot k_2 \cdot t$ and: $du = T_{BO} \cdot k_2 \cdot dt$:

$$-2 \cdot \int_0^t \left(\frac{1}{1 - T_{BO} \cdot k_2 \cdot t}\right) \cdot dt$$

$$= -\frac{2}{T_{BO} \cdot k_2} \int_0^t \left(\frac{1}{1-u}\right) \cdot du = \frac{2}{T_{BO} \cdot k_2}$$

$$\cdot \ln(1-u) = \frac{2}{T_{BO} \cdot k_2} \cdot \ln(1 - T_{BO} \cdot k_2 \cdot t)$$

$$-2 \cdot \int_0^t \left(\frac{1}{1 - T_{BO} \cdot k_2 \cdot t}\right) \cdot dt = \frac{2}{T_{BO} \cdot k_2} \cdot \ln(1 - T_{BO} \cdot k_2 \cdot t)$$

and finally: $ML_2 = \frac{-1}{T_{BO} \cdot k_2 \cdot (1 - T_{BO} \cdot k_2 \cdot t)} + \frac{2 \cdot \ln(1 - T_{BO} \cdot k_2 \cdot t)}{T_{BO} \cdot k_2} + t + \frac{1}{T_{BO} \cdot k_2}$ (11).

3. Application to Neves Corvo deposit

The Neves-Corvo ore deposit is located in the Portuguese province of Alentejo. Somincor (Sociedade Mineira de Neves-Corvo) is the operator. It is the largest massive sulphide Cu-Zn deposit in Europe and one of the largest in the world. Production started at the end of 1988 and copper concentrates have been exported throughout the world since January 1989 (De Asençao Guedes, 2004). Ore reserves are estimated at 1.4 billion t (Sáez and Moreno, 1997). The ore grade is variable but can reach 7.6% for copper and 2.5% for tin. The mineralization mainly consists of cassiterite, chalcopyrite, galena and sphalerite in a gangue of quartz, chlorite and sericite. Stockwerk is particularly rich in sulfosalts containing Cu, As, Sn, Co, Bi, Te (Se) and Ag (Ricour et al., 2003). The metal content of the deposit is about 250 000 t of Sn, 3.54 million t of Zn, 3,460,000 t of Cu, and 800 000 t of Pb (Ricour et al., 2003).

3.1 Materials and method

The materials (powders) used in this study were selected from seven stages of the mineral processing at the Neves Corvo concentration plant (Fig. 2). The samples were taken simultaneously. Samples and the corresponding residence time, flow rate, solid concentration in the pulp and Fe, S, Cu, Zn, Pb and Sn contents for samples S5 to S7 were provided by Somincor (Fig. 2, Table 1). Using the same approach as Lotter and Laplante (2007), sampling was carried out respecting Gy's minimum sample mass model. The masses are given in table 1. The streams sampled were chosen to guarantee maximum representativeness. The samples taken were then divided in a pulp divider before filtering and drying. A small part was sent to the ISO norm certified lab to be analyzed by Atomic Absorption. The assays are cross-checked with the online and inline analyzers.

The chemistry of the samples S1 to S4, were acquired by using a handheld XRF spectrometer. Before analysis, all rock powders (S1 to S7) were compacted into pellets using a Perkin-Elmer hydraulic press. To validate the results obtained on samples S1 to S4, the chemical composition of samples S5 to S7 obtained by portable XRF and given by Somincor were compared (Table 2, Fig. 3). The graphic in figure 3 illustrates the good correlation between the two sets of data: i;e. a linear correlation coefficient close to unity and regression lines through the origin with a slope close to unity. The results, with a confidence interval of 95% (i.e. two times the standard deviation) are given in table 2.

Table 1 presents the mineralogy at each step of the mineral processing of Neves Corvo plant. Since studied samples are very fine grained, the textures of the material are frequently difficult to identify. The internal textures of pyrite were studied after etching with nitric acid to enhance growth forms and contacts between different framboids. The term framboïdal was adopted by Rust in 1935 to describe a particular morphology of pyrite resembling a raspberry. Framboïdal texture is a spherical aggregate of sub-spherical pyrite microcrystals of uniform size (Wilkin and Barnes, 1997). Framboïdal pyrites are quite common in the deposit type

studied (volcanogenic massive sulphide) and therefore special attention was paid to their relation with other sulphides and their evolution over time. Framboïdal pyrites vary in size from tens to hundreds of microns. The more the mineral processing advances the identification of the texture of framboidal pyrites becomes more difficult due to finer particle size. Despite this limitation, we have still observed remnant framboïdal pyrites in the concentrate and in the final rejected fraction. This observation motivates the study of microtexture as a possible means of identification of the initial bulk ore.

3.2 Evolution of "memory loss" parameter (plm) during the mineral processing at Neves Corvo and "memory loss" (ML_{exp})

Using the portable XRF spectrometer ©Niton data, the "memory loss" parameter (plm) for Cu, Zn and Fe has been calculated, according to (1), for samples S1 to S6. The results are plotted in figure 4. The S7 sample, the final tailings, is not taken into account in this calculation. The experimental "memory loss" (ML_{exp}) has been evaluated using equation (3) for the three metals. Results are given in figure 4 and table 3.

As shown in table 1, the mineralogical composition of concentrate and final tailings points to a better recovery for chalcopyrite than for sphalerite and the values of ML_{exp} higher for Cu than for Zn (ML_{exp} are respectively equal to 14146 min and 3408 min) illustrate the difference between the recoveries of the two metals.

An estimation of the global kinetic rate of flotation for Cu and Zn has been done using equations (4) and (5). Since we only consider flotation kinetics, only the S4, S5 and S6 steps were considered (figure 5). Results are given in table 3. The global kinetic rate for Cu can be poorly described as of first order (correlation coefficient of 0.73) and is not consistent with a

second order (correlation coefficient of 0). For Zn, global kinetic rate appears more of first order (correlation coefficient of 0.91) than of second order (correlation coefficient of 0.65).

The discrepancy between the values of experimental memory loss (ML_{exp}) and those calculated from first order kinetic consideration (ML_1) (Table 3) can be interpreted in at least two ways:

(1) Calculations of ML_{exp} and ML_1 are performed assuming different behaviors of memory loss parameter (= pml_i) during mineral processing, respectively linear for ML_{exp} and exponential for ML_1.
(2) The order of the kinetic flotation is in the range between 1 and 2.

In order to improve the interpretation, the number of samples taken needs to be increased in the flotation part of the plant.

Whatever the reason for the difference between the values of ML_1 and ML_{exp}, these two parameters reflect the difficulty of determining the origin of a concentrate.

4. Conclusions

The experimental "memory loss" (ML_{exp}) characterizes a mineral processing at any given time and its calculation requires the chemical compositions and the minimum residence time at the different steps of mineral processing. This calculation is performed by evaluating the area between the experimental "memory loss" curve (ML_{exp}) and the "memory loss" curve in case of a totally inefficient treatment.

Work in progress attempts to describe the velocity of "memory loss" during mineral processing using the formalism of the Liapunov theory of stability (see for example Danilov, 2003).

The value of ML_{exp} estimates the difficulty of performing the inversion from the concentrate to the bulk ore, and thus the error associated with this inversion. As expected, the comparison between the "memory loss" for Cu and Zn at the Neves Corvo plant, shows that the experimental "memory loss" (ML_{exp}) is much more important for the main metal (Cu) than for the secondary elements (Zn). This result further emphasizes the importance of secondary elements in the traceability of concentrates.

The final aim of this study, which is a part of a comprehensive study on ore traceability, is to establish a database of the characteristic parameters of different mineral processing. Parameters to characterize a mineral process could be: mineralogical composition, identification of textural microfacies of target minerals, pseudo paragenetic sequence, and the contents and distribution of minor elements in targets minerals.

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FIGURE CAPTIONS

Figure 1 : Schematic plot illustrating the « memory loss » MLexp parameter versus the residence time

Figure 2: Simplified flow sheet of mineral processing of Neves Corvo mine. The stars represent the sampling points from S1 to S7. Residence time, flow rate and concentration in solid related to each sample are also reported.

Figure 3 : Comparison of Fe (circle), Cu (square) and Zn (star) content obtained by ©Niton and by XRF analyses of the mine laboratory. The comparison between the two analytical methods is based upon the three analyses provided par Somincor. Linear correlation coefficient R and equation of regression lines are given for the three analyzed metals.

Figure 4 : Plots representing the variation of the "memory loss" parameter during the mineral processing at Neves Corvo for copper, zinc and iron. The different steps are S1: Bulk ore, S2: Cone crusher discharge, S3: Rod mill discharge, S4: Ball mill discharge, S5: Rougher cell discharge, S6: Final concentrate. The time in squares corresponds to minimum residence time (in minutes). Gray areas represent experimental "memory loss" (ML_{exp}), which values are given.

Figure 5 : Plots illustrating the first (a) and second (b) order kinetics of copper in the flotation steps (S4, S5, S6) during the mineral processing of Neves Corvo mine.

Table 1 : Mineralogical composition and mass of each sample. The Fe, S, Cu, Zn, Pb and Sn contents provided par Somincor for samples S4 to S7 are also given.

Table 2 : Cu, Zn and Fe contents measured by ©Niton and XRF analysis (provided by the mine laboratory) and value of the corresponding « memory loss » parameter, calculated according to (1), for each step of the mineral processing of Neves Corvo. The number of analyses performed with ©Niton analyses is given. The metal content obtained by ©Niton is given with a confidence interval of 95% (i.e. two times the standard deviation).

Table 3 : Summary of parameters of the mineral processing of Neves Corvo mine. ML values are expressed in minutes.

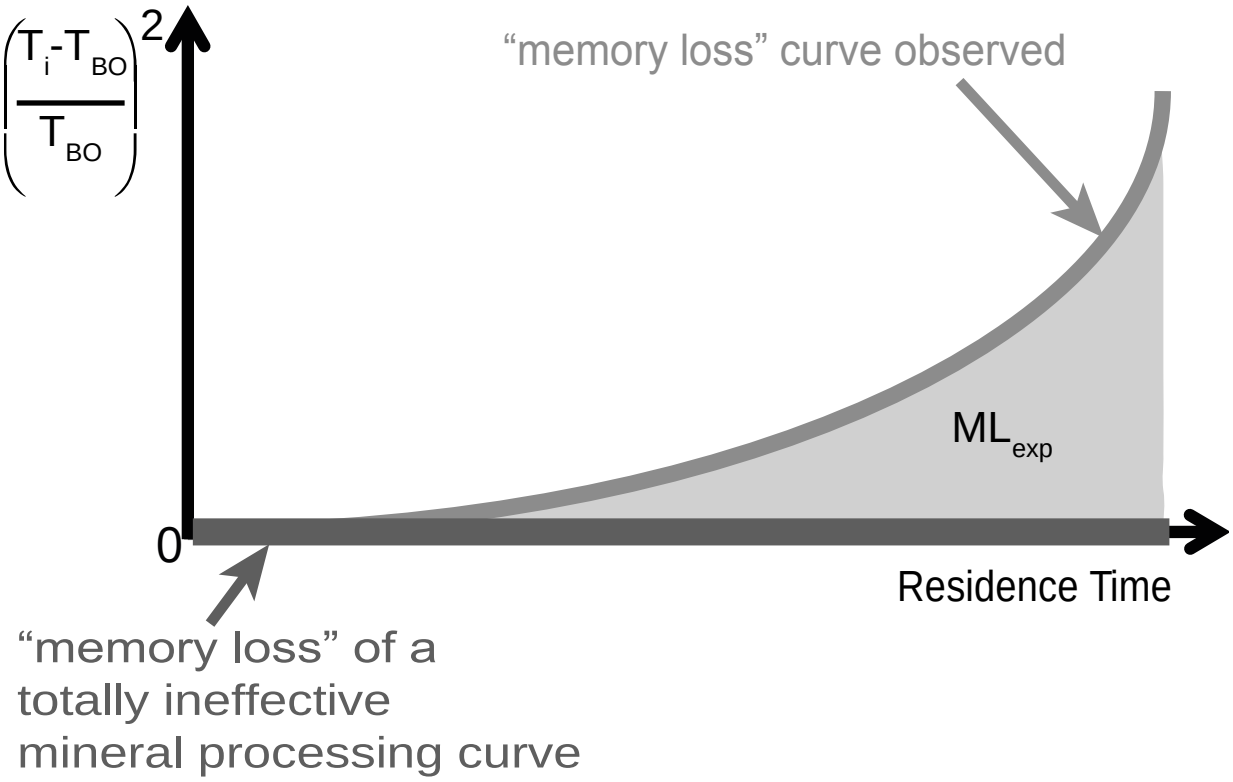
$\left(\frac{T_i - T_{BO}}{T_{BO}}\right)^2$
"memory loss" curve observed
ML_{exp}
0
Residence Time
"memory loss" of a
totally ineffective
mineral processing curve

Figure 1

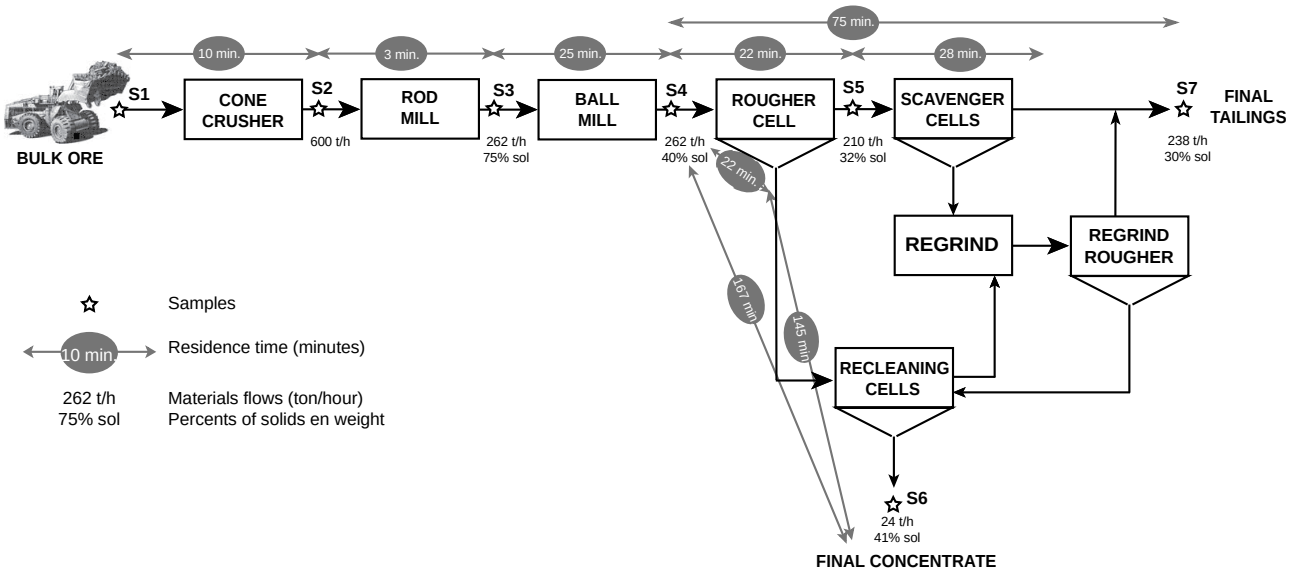
75 min.
10 min.
3 min.
25 min.
22 min.
28 min.
S1
CONE CRUSHER
S2
600 t/h
ROD MILL
S3
262 t/h
75% sol
BALL MILL
S4
262 t/h
40% sol
ROUGHER CELL
S5
210 t/h
32% sol
SCAVENGER CELLS
S7
238 t/h
30% sol
FINAL TAILINGS
BULK ORE
22 min.
REGRIND
REGRIND ROUGHER
167 min.
145 min.
RECLEANING CELLS
S6
24 t/h
41% sol
FINAL CONCENTRATE
Samples
10 min.
Residence time (minutes)
262 t/h
75% sol
Materials flows (ton/hour)
Percents of solids en weight

Figure 2

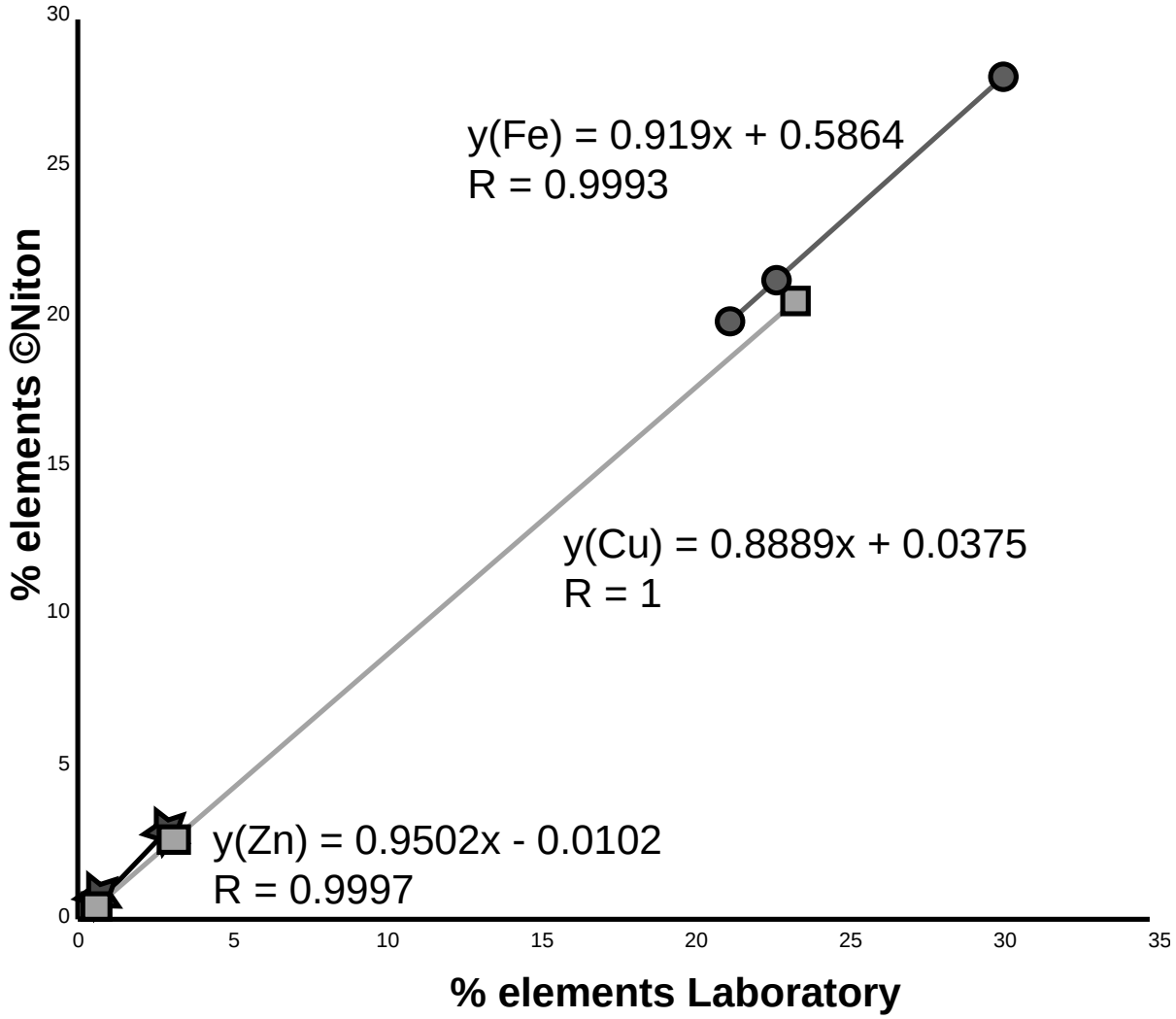
y(Fe) = 0.919x + 0.5864
R = 0.9993
y(Cu) = 0.8889x + 0.0375
R = 1
y(Zn) = 0.9502x - 0.0102
R = 0.9997
% elements ©Niton
% elements Laboratory
0
5
10
15
20
25
30
35

Figure 3

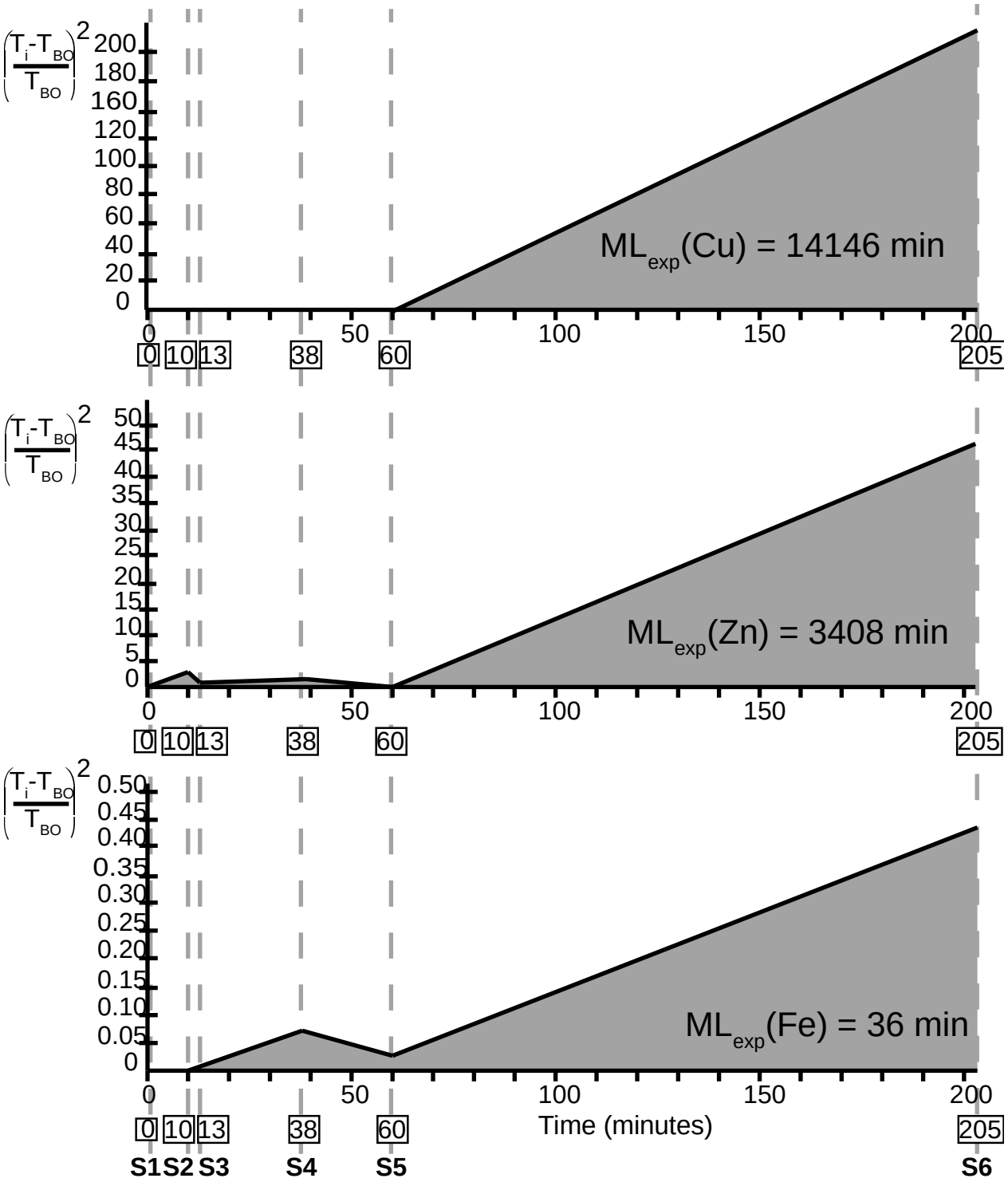
$\left(\frac{T_i-T_{BO}}{T_{BO}}\right)^2$
200
180
160
120
100
80
60
40
20
0
ML_{exp}(Cu) = 14146 min
0
50
100
150
200
0
10
13
38
60
205
$\left(\frac{T_i-T_{BO}}{T_{BO}}\right)^2$
50
45
40
35
30
25
20
15
10
5
0
ML_{exp}(Zn) = 3408 min
0
50
100
150
200
0
10
13
38
60
205
$\left(\frac{T_i-T_{BO}}{T_{BO}}\right)^2$
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
ML_{exp}(Fe) = 36 min
0
50
100
150
200
0
10
13
38
60
Time (minutes)
205
S1
S2
S3
S4
S5
S6

Figure 4

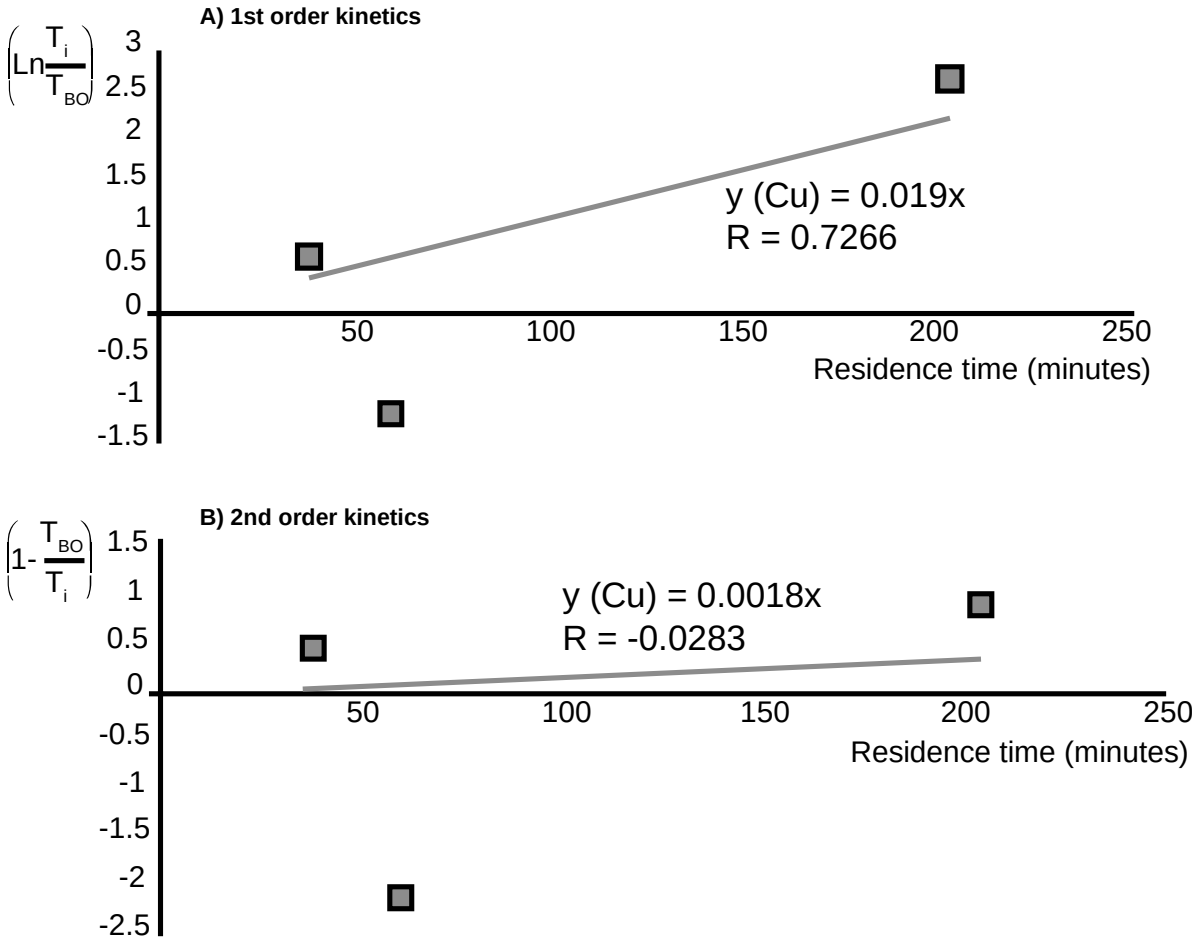
A) 1st order kinetics
$\left(Ln\frac{T_i}{T_{BO}}\right)$
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
y (Cu) = 0.019x
R = 0.7266
50
100
150
200
250
Residence time (minutes)
B) 2nd order kinetics
$\left(1-\frac{T_{BO}}{T_i}\right)$
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
y (Cu) = 0.0018x
R = -0.0283
50
100
150
200
250
Residence time (minutes)

Figure 5

Samples	AA Very abundant	A Abundant	F Frequent	R Rare	Chemical composition Mine laboratory	Mass of sample (in grams)
S1 **Bulk ore**	pyrite chalcopyrite sphalerite			stannite arsenopyrite cassiterite		19100
S2 **Cone crusher discharge**	pyrite chalcopyrite	sphalerite		stannite arsenopyrite cassiterite		17200
S3 **Rod mill discharge**	pyrite chalcopyrite	sphalerite		stannite arsenopyrite cassiterite		2083.9
S4 **Ball mill discharge**	pyrite	chalcopyrite	sphalerite	stannite arsenopyrite cassiterite	22.54% Fe, 13.78% S, 2.92% Cu, 0.77% Zn, 0.20% Pb, 0.16% Sn	479.31
S5 **Rougher cell discharge**	pyrite		chalcopyrite sphalerite	arsenopyrite	21.07% Fe, 11.36% S, 0.52% Cu, 0.49% Zn, 0.13% Pb, 0.13% Sn	514.6
S6 **Final concentrate**	chalcopyrite	sphalerite	pyrite	stannite cassiterite	30% Fe, 29.98% S, 23.14% Cu, 2.94% Zn, 0.67% Pb, 0.35% Sn	613
S7 **Final reject**	pyrite arsenopyrite			sphalerite chalcopyrite	22.31% Fe, 13.02% S, 0.67% Cu, 0.58% Zn, 0.14% Pb, 0.13% Sn	600.6

Table 1

	S1 Bulk ore	S2 Cone crusher discharge	S3 Rod mill discharge	S4 Ball mill discharge	S5 Rougher cell discharge	S6 Final concentrate
Minimum residence time	0	10	13	38	60	205
Number of analyses performed with ©Niton	7	5	5	5	5	5
Cu "memory loss" parameter = pml(Cu)	0	0.61	0.95	0.92	0.46	195.06
Cu content with a confidence interval of 95% measured by ©Niton	1.38 ± 0.12	2.45 ± 0.02	2.72 ± 0.26	2.7 ± 0.02	0.44 ± 0.02	20.6 ± 1.07
Cu content measured by mine Laboratory				2.92	0.52	23.14
Zn "memory loss" parameter = pml(Zn)	0	2.62	0.88	1.23	0.44	46.15
Zn content with a confidence interval of 95% measured by ©Niton	0.36 ± 0.04	0.93 ± 0.02	0.69 ± 0.1	0.75 ± 0.03	0.43 ± 0.01	2.78 ± 0.14
Zn content measured by mine Laboratory				0.77	0.49	2.94
Fe "memory loss" parameter = pml(Fe)	0	0	0.04	0.07	0.03	0.43
Fe content with a confidence interval of 95% measured by ©Niton	16.98 ± 1.34	17.47 ± 1.12	20.4 ± 1.15	21.47 ± 0.18	19.81 ± 0.25	28.13 ± 1.37
Fe content measured by mine Laboratory				22.54	21.07	30

Table 2

	All steps of the process	Kinetics first order	Kinetics second order
Cu	ML_{exp}=14146	λ_1=0.011 R=0.53 ML_1=5819	λ_2=0.013 R=-8.10^{-4}
Zn	ML_{exp}=3408	λ_1=0.0098 R=0.83 ML_1=1818	λ_2=0.011 R=0.43
Fe	ML_{exp}=36	λ_1=0.0026 R=0.71 ML_1=27	λ_2=0.0027 R=0.47

Table 3